International Journal of the Commons
Vol. 10, no 1 xxxx 2016, pp. x–x
Publisher: Uopen Journals
URL:http://www.thecommonsjournal.org
DOI: 10.18352/ijc.606

ISSN: 1875-0281

# Managing the commons: a simple model of the emergence of institutions through collective action

Amineh Ghorbani
Faculty of Technology, Policy and Management, Delft University of Technology, The Netherlands
a.ghorbani@tudelft.nl

Giangiacomo Bravo
Social Studies Department, Linnaeus University, Sweden
giangiacomo.bravo@lnu.se

**Abstract:** In this paper we present an abstract replication of institutional emergence patterns observed in common pool resource (CPR) problems. We used the ADICO grammar of institutions as the basic structure to model both users' strategies and institutions. Through an evolutionary process, users modify their behaviours and eventually establish a management institution for their CPR system, leading to significant benefits both for them and for the commons as a whole. We showed that, even with a high level of abstraction, by taking an evolutionary perspective and using the ADICO structure, we are able to observe common institutional patterns. We confirmed that, even within this simplified environment, institutions significantly contributed to the sustainable management of common-pool resource systems.

**Keywords:** Common pool resource, emergence, evolutionary modelling, institutions, self-organization

**Acknowledgment:** This research has been partly financed by a grant of the Energy Delta Gas Research (EDGaR) program, B2 (TransGasID). EDGaR is co-financed by the Northern Netherlands Provinces, the European Fund for Regional Development, the Ministry of Economic Affairs of the Netherlands and the Province of Groningen. This research also benefited from the Linnaeus University Strategic Internationalization Fund (*Strategiska internationaliseringsmedel*) 2013. We finally acknowledge the constructive comments received from three anonymous referees and from the participants in the 2014 Social Simulation conference and the 2015 IASC global meeting.

## 1. Introduction

Four decades of research have shown that Hardin's *Tragedy of the Commons* (Hardin 1968), although frequently occurring in open access resources, can be avoided thanks to the building of carefully-designed endogenous institutions (Ostrom 1990, 2005; Anderies and Janssen 2013). However, the specific processes leading to institutional change are often difficult to study in the field due to the large number of factors potentially involved, and because such processes often occur on temporal scales beyond the scope of most social science research (Poteete et al. 2010). Laboratory experiments may offer a way out of the problem, and they indeed significantly contribute to our understanding of the dynamics of common-pool resource (CPR) situations (Ostrom 2006). Nevertheless, the number and nature of factors that can be reasonably tested in the lab are limited. For instance, it is difficult to design experiments involving long-term interactions among participants or doing studies needing large samples of subjects. For these reasons, we need to expand our understanding of the development of commons management institutions with more complex methods alongside current lab and field studies.

Agent-based models (ABM) represent an interesting alternative to both methods. Their main advantage is that they allow to design virtual experiments using a more flexible set of conditions than what is feasible in the lab and to analyse their long term dynamics more easily than what is possible in the field (Poteete et al. 2010; Bravo 2011; Bravo et al. 2012). Using ABMs, it is indeed possible to design complex models that are able to capture the effect of a large number of factors on CPR management. The outcomes may be subsequently compared with empirical findings to test the models ability to reproduce patterns and dynamics observed in the real world (Railsback and Grimm 2005; Janssen and Ostrom 2006b; Squazzoni 2012).

In this work, we present an ABM designed to replicate patterns of institutional emergence commonly observed in the field. The main goal of this preliminary model is to show that it is possible to model an institution emerging from the interaction of simple agents, without assuming advanced cognitive capacities for them. Although only at the first stage, the current model already is able to illustrate the added value of having self-governing institutions in the system by comparing scenarios with and without institutions. Its main interest relies in a dynamic description of the mechanisms through which well adapted institutions can emerge from the strategies of agents through a cultural evolutionary process. This will allow to go on with its progressive complexification following a research programme that will proceed through (i) the incorporation of more elements, notably cheating and sanctioning arrangements, in the model (ii) the validation of the model using cross-sectional and longitudinal data of real-world CPR institutions, and (iii) the application of the validated model to specific cases of CPR management to elaborate credible scenarios of alternative management options.

The model is based on the “grammar of institutions”, first introduced by Crawford and Ostrom (Crawford and Ostrom 1995), and takes an implicit evolutionary approach to explain the dynamics of CPR management institutions as emerging from the beliefs and actions of users. This is in line with what we have learned from decades of commons research, including Ostrom’s work (Ostrom 1990, 2005; Ostrom et al. 1994), and from institutional economics (e.g. North 1990, 2005). In our model agents represent resource users, who are initially endowed with a set of behavioural strategies structured upon the ADICO grammar but can also learn by copying others or by exploring new possibilities. Moreover, when unsatisfied with the current state of affairs, they can engage in collective action in order to collectively manage their resource through an institution defined as an ADICO rule (see Crawford and Ostrom 1995). The model is currently in its first phases of development. Yet, it is already able to replicate common dynamics of institutional emergence and allows us to reach a better understanding of the process underlying the development of CPR management institutions. Notably, it shows that institutions favouring CPR management can emerge through collective behaviour even without assuming advanced cognitive capacities for the agents.

The structure of this paper is as follows. Section 2 introduces the definition of institutions that will be used in the paper and provides background on common pool resource management problems. Section 3 defines our ABM which allows for the emergence of institutions for CPR management. Section 4 discusses simulation results. Finally, Section 5 gives the concluding remarks.

## 2. Background

### 2.1. Common-pool resource systems

Common-pool resources are natural or man-made resources shared among different users (Ostrom 1990). This produces competition that often (although not necessarily) leads to their degradation or even to destruction. Many natural resources fall in this category and are today “chronically” overused. Examples are forests, fisheries, water basins and even the atmosphere.

Formally, the expression *common-pool resource* refers to a class of goods defined by two characteristics: a difficult *excludability* of potential beneficiaries and a high degree of *subtractability* (i.e. rivalry of consumption) (Ostrom et al. 1994). Thus, the CPRs share characters with both private and public goods, namely a high subtractability with the former ones and a low possibility of exclusion with the latter ones. This makes the management of CPRs especially complex: as in the private good case, the consumption of resource units (e.g. extraction of timber from a forest, of water from a basin, etc.) by one user reduces the total quantity of units available to the other ones; as in the public good case, it is difficult to prevent any user from continuing to subtract units from an endangered resource (e.g. the ocean fisheries). This led Hardin to picture the commons problem as a social dilemma in his famous article *The Tragedy of the Commons* (Hardin 1968). Formally, this can be seen as a *n* players version of the Prisoner's dilemma or, more properly, as a CPR game, as first proposed by Walker and colleagues (Walker et al. 1990). In both cases, no user has rational incentives to limit his/her consumption and, hence, the possibility to avoid the resource degradation or destruction is extremely low.

Subsequent authors followed Hardin in presenting CPR management as a social dilemma and in formalizing it using different variations of the games above (Ostrom et al. 1994; Falk et al. 2002). These all share the idea that the rational equilibrium of the game is well below the collective optimum theoretically achievable by restricting resource use to a sustainable level. Nevertheless, in contrast with theoretical predictions, empirical research has shown that successful management of the resources can be achieved by building endogenous institutions (e.g. Ostrom 1990; Ostrom et al. 2002; Anderies and Janssen 2013). More specifically, the "tragedy" is avoided thanks to institutions that define clear exploitation rights and create incentives to prevent resource overuse. In other words, the tragedy of the commons is the tragedy of open-access resources, not necessarily of well managed CPRs.

Assuming institutional development as the main way out of the dilemma, the question becomes how to favour this process. Empirical research trying to answer this question has been summarized in Ostrom's "diagnostic approach" (Ostrom 2007), which includes a large number of factors potentially affecting the outcome of interaction in CPRs situations. Nevertheless, selecting which factors are actually relevant in a given situation remains a non-trivial task. What is still missing in guiding this choice is a clearer picture of the mechanisms behind the emergence of institutions in CPR situations. ABMs represent an appropriate tool for this endeavour thanks to their capacity of linking the micro and macro-levels of social behaviour (Hedström 2005; Squazzoni 2012). However, a rigorous characterization of institutions becomes crucial to fully exploit the analytical capacity of these models.

### 2.2. The ADICO grammar of institutions

In economics, institutions are usually defined as "the set of rules actually used by a set of individuals to organize repetitive activities that produce outcomes affecting those individuals and potentially affecting others" (North 1990). Institutions enable interactions, provide stability, certainty, and form the basis for trust. They may however, keep people in unsustainable behaviours or lead to biased power relations. The *ADICO grammar of institutions* (Crawford and Ostrom 1995; Ostrom 2005) is used to structure and analyse institutions.

ADICO structures institutional statements into five components: *A*ttributes, *D*eontic, a*I*m, *C*ondition, and sanction (*O*r else). This structure summarizes institutional statements, facilitating the understanding of the formation and evolution of institutions (Ostrom 2005).

***Attributes***

Attributes describe the participants in the situation to whom the institutional statement applies. For example, an attribute of an ADICO can be a 'student'.

***Deontic type***

Deontic operators are *obligated*, *permitted* and *forbidden*. When an institutional statement has the deontic type 'obliged' the person *must* perform the action associated to the institution. For example, "a student is obliged to attend 50% of class A in order to be able to sit the exam". On the contrary, for institutions with the deontic type 'forbidden', actors are not allowed to perform the action associated to the institution. For example, "a student is not permitted to take a course twice". The deontic type 'permission' constitutes the action related to the institution or grant rights to participants with certain properties to perform an action. For example, "a student with GPA above 9 is permitted to take more than 100 credits per semester".

***aIm***

The aim component describes the action or outcome to which the institutional statement applies. In order for an institution to influence behaviour, individuals must have a choice concerning its 'aim'. In other words, prescribing an action or outcome only makes sense if its negation is also possible. In the above mentioned examples of institutions, "take course", "sit exam" and "take credit" are the aims of those institutional statements.

***Condition***

Conditions are the set of parameters that define when and where an ADICO statement applies. If there is no condition stated, it implies that the statement holds at all times.

***Or else***

'Or else' is the consequence of non-compliance to an assigned institutional statement. A common type of 'Or else' is a sanction.

It is worth noting that following (Crawford and Ostrom 1995), a situation where there is no institution is formally equivalent to one where there is a rule stating that everything is permitted. Using the ADICO structure, the latter translates into A=all, D=permitted, I=everything, C=always, O=non relevant. This means that institutional emergence and change can be studied using the same framework as a situation where an initial situation where everything is permitted is modified into more stringent rules. Note that the scope of the institutions that can emerge from the agents' choices in the model only covers the operational rules (Ostrom 2005), while collective-choice rules are exogenous and depend on the model parameter setting (see Section 3).

Note that in the current version of the model agents always comply with the institution (see Section 5 for a discussion about future development of the model relaxing this assumption). This means that the *Or else* component of the framework becomes non relevant as it only applies in case of cheating. Nonetheless, from now on we will use the expressions *institution* to refer to a complete ADICO structure even if, formally, only the ADIC components are implemented in the current model.[1] We will also use the wording “no institution” to refer to the situation where agents are free to use their individual strategies and, hence, everything is permitted.

## 3. An ABM of emerging institutions

### 3.1. Agent-based modelling of CPR situations

Agent-based modelling is a well-established simulation approach that has proved to deliver valuable insights into complex problems (Epstein 1999; Axtell 2000). ABMs are computational simulations of individual social entities who interact among themselves and with their environment. The main benefits of ABM that distinguish this approach from other methods are its ability to:

- Capture emergent patterns and structures from bottom-up individual interactions (Macy and Willer 2002).
- Create a natural representation of a system based on individuals and assess their effects on the system as a whole (Bonabeau 2002).
- Incorporate adaptive behaviour and the heterogeneity of system components (Balbi and Giupponi 2009).

Given the nature of a common-pool resource and the dynamics of its users behaviours, agent-based modelling is an insightful simulation tool to study the dynamics of institutional developments in such systems. Several ABMs previously explored CPR management problems. Deadman et al. (2000) were the first to model agents to replicate the findings of commons experiments, including the strong effect of communication on cooperation. Jager and Janssen (2003) used a social psychology framework to build cognitively complex agents, showing that imitation is a key mechanism to explain the spreading of unsustainable behaviours (i.e. high resource consumption levels). Janssen and Ostrom (2006a) explicitly modelled the emergence of institutions in a population of heterogeneous agents. In their model, the CPR has a “physical structure” similar to that subsequently used as experimental platform (Janssen et al. 2008). Bravo (2011) employed ABM to study the relation between agents’ beliefs and institutional emergence. Finally, Smajgl et al. (2008) were the first to apply the ADICO framework to model rule changes in resource dilemmas.

[1] Crawford and Ostrom (1995) refer to a statement having an ADIC structure as a social norm.

### 3.2. Model overview

The model presented here is implemented in Netlogo (Wilensky 1999), a software platform for agent-based modelling that is increasingly used for both educational and research purposes in the social and natural sciences (e.g. Railsback and Grimm 2012; Wilensky and Rand 2015). The model takes the ADICO sequence as a starting point to allow institutions to emerge and evolve in an abstract CPR system. The users of the CPR (i.e. the Attribute in the ADICOS sequence) are modelled as agents. These agents consume the resource by taking certain amounts and in turn gain 'energy' from their consumption. We assume that one unit of resource is the same as one unit of agent energy.

To model the users' consumption patterns, the agents are given the flexibility to choose when to use the resource and how many resource units to appropriate each time they use the resource. In ADICO terms, this is equivalent to a *strategy* composed of the following elements: A=myself, D=must, I=appropriate *n* resource units, C=at the time when the condition *c* is met. To model this strategy, we make a list of actions (the number of resource unit to consume) and a list of conditions that the agents can choose from. They combine their selected action and condition pair to form their individual strategies. For example, strategies can take the form "Consume 5 resource units when my energy is lower than zero" or "Consume 10 resource units every 20 time steps".

Agents can select their strategies in two different ways: (i) by trying new strategies by combining new action and condition pairs, and (ii) by copying their most successful neighbours (i.e. the one with highest energy). The agents choose either of these two methods based on a random proportional probability. They only change their strategies when their energy level is below 0 which models a situation where the number of units extracted from the resource are not able to meet the "livelihood needs" of the agents. The rationale here is that agents performing poorly will try to change their behaviour, either by imitating others or by innovating, in order to improve their welfare.

At regular intervals, agents have the opportunity to decide about introducing an institution if it does not exist yet, or modifying the existing one. This mimics the regular commoners meetings of real-world commons institutions. Even during these meetings, institutional change only takes place if the number of agents dissatisfied with the current institution is higher than a certain threshold. In other words, we assumed that: (i) agents whose energy is negative become dissatisfied with the current institution and vote for a change; (ii) if their proportion is greater than the `threshold for institutional change` (i.e. they reach a certain qualified majority) their vote is successful and a new institution is established.

The institutional change procedure works as follows. Every agent proposes its own individual strategy as one that should be taken as the institution. The strategy that is proposed most frequently (i.e. the modal strategy), is then *selected* as the institution. From this point onwards, every agent *must* (D in the ADICO sequence) and *will* follow the institution rather than their own individual strategies because no cheating is possible[2]. However, individual strategies continue to change following the same rules as before (i.e. copying or innovating). Even if this holds no practical consequences in the immediate, it mimics the change of opinions of commoners about the best way to manage the resource. The changes accumulate and eventually aggregate into a new modal strategy leading to a transformation of the institution at a later point in time.

### 3.3. Model components

The model consists of the following components:

*Agents*. Each agent has two parameters that are kept track of: energy level and individual strategy. To allow agents to copy their most successful neighbour's strategy, they are modelled as nodes in a social network defining their neighbourhood. The network is currently defined as having one of the following two different structures:

- random network: In a random network, each node is randomly connected to X number of other nodes where X is given by the modeller.
- small-world network: In a small-world network most nodes are only locally connected to close neighbours but a few nodes hold "long distance" connections allowing relatively short path lengths between any couple of randomly selected nodes (Watts and Strogatz 1998). The energy hold by agents is an abstract representation of their level of welfare. Is can be seen as their wealth, in non-monetary (resource units) or monetary (the value of each resource unit) terms. What is worth noting is that the absolute energy levels hold no substantial meaning. What matters in the model is the distance from a given "satisfaction threshold" (arbitrarily placed at the zero energy level), which determines whether the agents will try to modify their individual strategies or start collective action to change the institution. This satisfaction threshold can be seen as a level of wealth above which agents are able to reach a decent welfare level and do not "feel" the need to change.

*Resource*. We assume that there is one single resource that is shared between agents in the simulation. The resource is renewable and provides resource units to agents (translated into energy). In each time step it (re)grows at a rate given by a logistic function with two parameters: the carrying capacity $K$ and the reproduction rate $r$, which represents the maximum proportional increase of the resource in one time step. The specific function used is a standard discrete-time logistic. The increase $\Delta R$ of the resource $R$ at time $t$ is given by:

---

[2] This assumption will be relaxed in future versions of the model. See Section 5 for a discussion of this point.

$$\Delta R = rR\left(1 - \frac{R}{K}\right) \tag{1}$$

At the beginning of the simulation the resource is set at carrying capacity, while it subsequently changes depending on the amount harvested by agents and on equation (1).

*ADICO components*. These are included in the model as follows:

- *Attributes*: The relevant statements apply to all agents in case of the establishment of an institutions.
- *Deontic*: The agents always comply with the institutions. Therefore, we can assume that the deontic is always of the 'obliged' type.
- *aIm*: We assume that all the actions an agent can possibly take are stored in a list. These actions are related to the common resource exploitation. The actions also influence the amount of energy the agents gain. For simplicity, we also assume that the number of units extracted from the resource is equal to the energy gained by the agent. For example, `consume5` implies that the agent gains 5 units of energy, while the resource is decreased by 5 unit. There is also one action that does not influence the resource, but reduces the amount of agent energy (`consume-5`). This action is included in the action list to represent possible losses that an agent may face (e.g. fishers losing their boat while trying to fish during a storm).
- *Condition*: We assume that all the conditions an agent can possibly consider are stored in a list. The conditions specify when and where the agent is allowed to perform its selected action. At a given point in time, each agent has only one action-condition pair.
- *Or else*: We assume that all agents follow the rule when an institution is in place. As a consequence, this component becomes non-relevant.

### 3.4. Institutional change

From the point where an institution is selected by the agents, individual strategies will no longer be followed until the end of the simulation. At any point in time after that, there will always exist one institution that needs to be followed by every agent. The institution is selected by a majority vote, as explained above. The voting procedure occurs at regular intervals, given by the `institutional emergence time` parameter, mimicking the regular commoners meetings of real-world commons institutions. During these meetings, institutional change only takes place if the number of agents having an energy level $< 0$ is higher than a certain `threshold for institutional` change (see Table 1). Note that the `institutional emergence time` and the `threshold for institutional` change parameters represent the model equivalent of the *collective-choice arrangements* of real communities as described within the IAD framework (Ostrom 2005).

*Table 1: Experimental setup.*

| Parameter | Values |
|---|---|
| Actions | consume $[(n\times2),1<n<10]$, [–5] |
| Conditions | (ticks mod 3)=0, (ticks mod 2)=0, energy <= 0, (ticks mod 20)=0, (ticks mod 250)=0, true (always) |
| Carrying capacity ($K$) | 5000–20,000 (step 1000) |
| Growth rate ($r$) | 0.1–0.5 (step 0.2) |
| Number of agents | 100 |
| Energy-consumption | 1, 5, 10 |
| Innovation rate | 0.05–0.1 (step 0.05) |
| Threshold for institutional change | 0.4. 0.6, 0.8, 1 |
| Institutional emergence time | 50, 100, 200, 500, 1000 |
| Number-of-links | 2 |
| Rewire-prop | 0.05 |

### 3.5. Simulation procedure

The simulation, depicted in the flowchart in Figure 1, is described below:

- Initialization:
  1. One hundred agents are created and located in the network.
  2. The resource is initialized equal to the carrying capacity ($K$).
- Initial strategy setup: each agent randomly selects a strategy, i.e. combination of one random action and one random condition;
- Procedures occurring in every time step:
  1. Agents lose energy
  2. The resource grows (explained above)
  3. Action execution: The type of procedure to be executed by the agents (i.e. individual strategy, or institution) is selected based on `institutional emergence time` and whether an institution is already present:
     - Individual-based action
       (a) agents gain new energy by exploiting the resource according to their own strategies;
       (b) each agent checks its current energy level; if it is below 0, it chooses a different action-condition combination for the next iteration based from the following two options:
         i. innovation: with a given probability (Table 1, `innovation rate`), the agent chooses a new action-condition pair similar to the beginning of the simulation;
         ii. copying: otherwise, if the agent will not be innovating (given the probability) the agent instead chooses the action-condition of the most successful agent (i.e. one with highest energy) in his neighbourhood.
     - Institutional emergence and change: If a certain proportion of agents (`threshold for institutional change`, Table 1) has

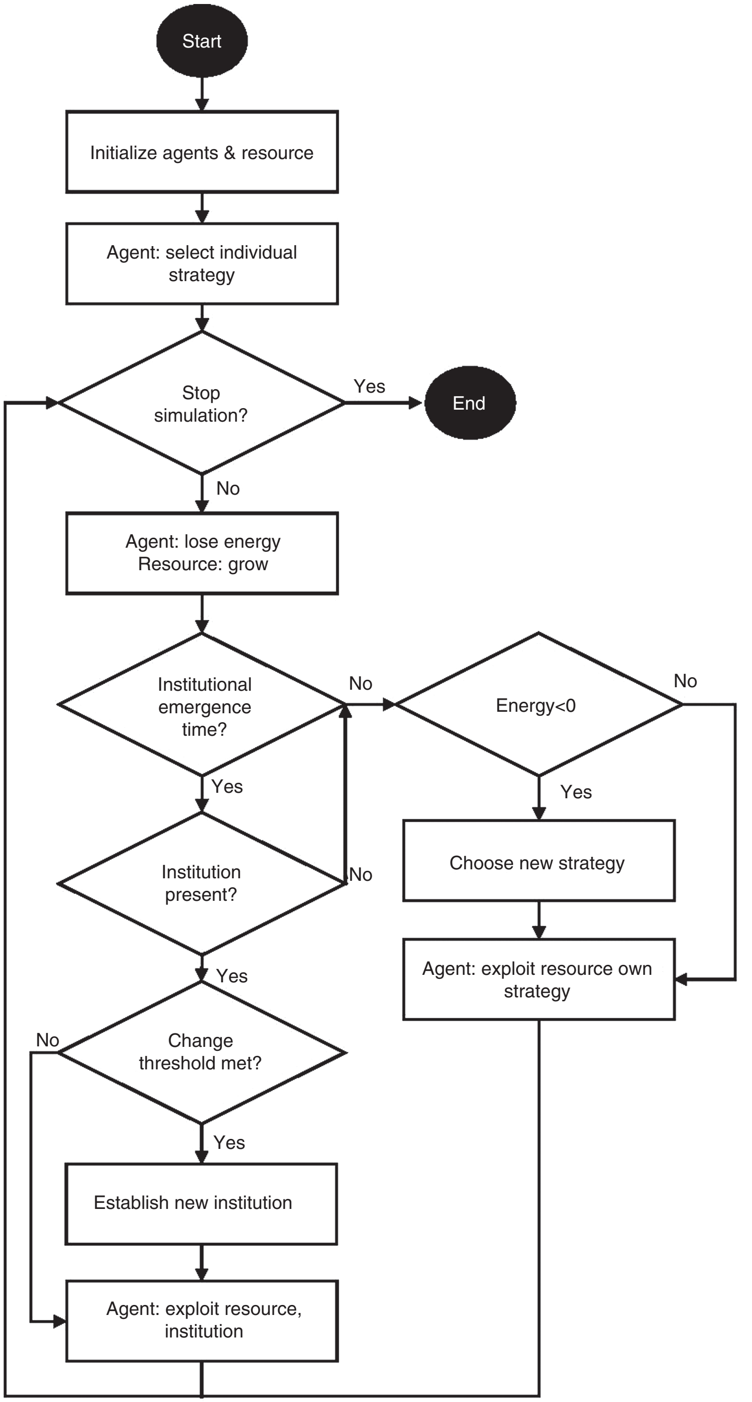


*Figure 1: The simulation procedure.*

energy below zero, there is call for institutional change. The most frequently used action-condition pair is selected as a new institution. From this point, the agents must comply with the institution, rather than performing their own action-condition pairs.

- The simulation ends after 2000 iterations or when the resource completely runs out.

### 3.6. Simulation setup

The goal of this preliminary model is to see whether it is possible to replicate the qualitative dynamics of empirical CPR systems using an abstract model of institutional emergence and evolution. More specifically, we compared the outcomes of the CPR system under the institution and no-institution conditions. In the first case, the agents can (even if do not have to) endogenously decide the operational rules to manage their commons using exogenously given collective-choice rule given by the parameter setting. In the second case, they only follow their individual strategies. The underlying question is whether the agents and the resource are better off, when the possibility to collectively select the resource management rules is present.

Table 1 shows the experimental setup, including the values used for the parameters introduced in the previous section. The actions are all in the form of consume X where either $2<x<20$ or $x=-5$ representing energy loss. the condition are either related to time (e.g. *ticks mod* 3=0) or related to the energy of the agents (e.g. *energy*<=0). The energy consumption of the agents has three values: 1, 5 and 10. The ratio of agents innovation instead of copying others is captured with the 'innovation rate' parameter. If the proportion of agents with negative energy is above `threshold for institutional change` (0.4. 0.6, 0.8, 1) and the iteration of the simulation is a factor of `institutional emergence time` (50, 100, 200, 500, 1000) the institutional change procedure is triggered. Finally, the `number-of-links` and `rewire-prop` are used to configure the network.

The parameter sweep resulted in 3240 runs which were repeated 100 times, leading to a total of 324,000 runs. Half of these runs allowed an institution to emerge, while the other half were without this possibility. For each run, the average energy of the agents, the average amount of resource, and the final selected institution were recorded.

## 4. Results

### 4.1. Resource and energy

The introduction of the institution positively affects both the amount of resource in the system and agents' energy. This remains true also controlling for the other simulation parameters, as shown by the ordinary least square (OLS) regression results presented in Tables 2 and 3. All parameters except the mutation rate have a significant effect on both dependent variables. As expected., the resource carrying capacity and renewal rate positively affect both the amount of resource available

*Table 2: OLS on the amount of resource remaining at the end of the simulation.*

| | Estimate | Std. error | t-Value | Pr(>\|*t*\|) |
|---|---|---|---|---|
| (Intercept) | –4626.0191 | 38.1777 | –121.17 | 0.0000 |
| Institution | 3516.6743 | 15.8985 | 221.20 | 0.0000 |
| *K* | 0.5148 | 0.0013 | 403.87 | 0.0000 |
| *r* | 14135.1495 | 46.7691 | 302.23 | 0.0000 |
| Energy consumption | –56.1966 | 2.1591 | –26.03 | 0.0000 |
| Institutional emergence time | –1.1240 | 0.0226 | –49.71 | 0.0000 |
| Mutation rate | 9.6372 | 215.9067 | 0.04 | 0.9644 |
| Threshold institutional change | –3530.4305 | 35.5500 | –99.31 | 0.0000 |
| $R^2$ | 0.4966 | | | |
| *F*(7,320752) | 4.52e+04 | | | 0.0000 |

*Table 3: OLS on the amount of agents' energy at the end of the simulation.*

| | Estimate | Std. error | t-Value | Pr(>\|*t*\|) |
|---|---|---|---|---|
| (Intercept) | –607.8326 | 16.1403 | –37.66 | 0.0000 |
| Institution | 58.8458 | 6.7214 | 8.76 | 0.0000 |
| *K* | 0.0915 | 0.0005 | 169.87 | 0.0000 |
| *r* | 3767.1631 | 19.7725 | 190.53 | 0.0000 |
| Energy consumption | –238.5417 | 0.9128 | –261.33 | 0.0000 |
| Institutional emergence time | –2.5759 | 0.0096 | –269.47 | 0.0000 |
| Mutation rate | –49.3257 | 91.2786 | –0.54 | 0.5889 |
| Threshold institutional change | –60.1269 | 15.0294 | –4.00 | 0.0001 |
| $R^2$ | 0.3913 | | | |
| *F*(7,320752) | 2.945e+04 | | | 0.0000 |

and the agents' energy, while the energy consumption negatively affects them. Especially interesting is to note that both the institutional emergence time and the proportion of agents needed to change the institution negatively affect both indicators. This means that the harder for agents to craft their institution the worse will the institution itself work; a finding that is consistent with the third of Ostrom's design principles ("collective-choice arrangements") stating that the resource users should be able to participate in practice in the establishment of the management rules. In practice here means at time intervals that are not too large and with a majority rule allowing them to actually change the institution when needed (Ostrom 1990, 93–94).

Although, on average the agents are better off when institution building is allowed, they do not necessarily reach an optimal situation. In most cases, the selected institution actually led to a condition when the available energy was below what the agents could have theoretically obtained from the resource. In a few cases, this was even below the energy gathered under the same parameter configuration in the no-institution condition. This is clear in Figure 2, which shows the average amount of energy and resource at the end of the simulation under all the different institutional arrangements selected by agents.

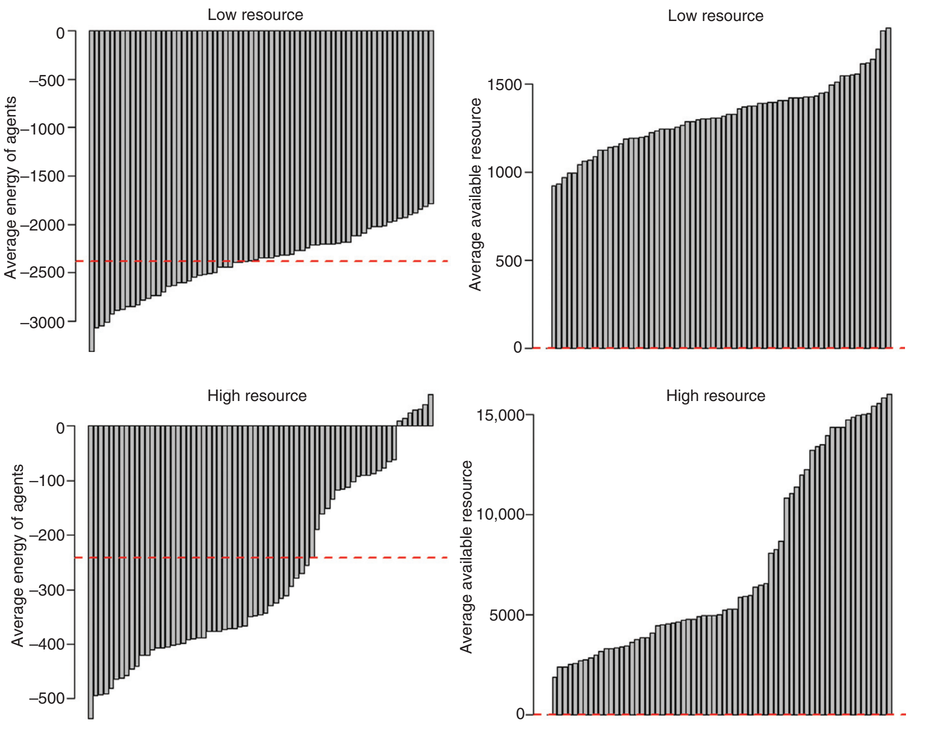


*Figure 2: Average energy of agents and resource left at the end of the simulation under various institutional arrangements in low and high resource conditions. Each bar corresponds to the outcome of one institutional arrangement. Low resource is defined as K=5000, r=0.1 and energy. consumption=10. High resource is defined as K=20,000, r=0.1 and energy.consumption=1. The dashed red lines represent the average energy and resource under the same parameter configurations in the no institution condition.*

To simplify the analysis, we selected two examples of resource condition characterized by difficult resource management (low carrying capacity and high energy consumption) and easier management (high carrying capacity and low energy consumption) respectively. Note that the extreme abundance condition ($K$=20,000, $r$=0.5) was not included in the analysis since the management of the resource under an open access rule was effective enough and agents never implemented a stricter institution (see Table 4 below).

Under all the selected institutions, the state of the resource at the end of the simulation was instead better than the no-institution case (Figure 2). This is quite interesting since it implies that the agents never chose an institution that would result in them using the resource more than in the open access situation. It is also worth noting that, under most of the selected institutional arrangements, the difference between the open-access and the regulated condition was quite dramatic, with the resource exploited at low to sustainable levels under all of

*Table 4: Modal institution for each combination of K, r and energy consumption.*

| *K* | *r* | Energy consumption | Selected institution |
|---|---|---|---|
| 5000 | 0.10 | 1 | [“eat 2” “energy <= 0”] |
| 10,000 | 0.10 | 1 | [“eat 2” “(ticks mod 2)=0”] |
| 20,000 | 0.10 | 1 | [“eat 18” “energy <= 0”] |
| 5000 | 0.20 | 1 | [“eat 4” “(ticks mod 3)=0 ”] |
| 10,000 | 0.20 | 1 | [“eat 2” “(ticks mod 2)=0”] |
| 20,000 | 0.20 | 1 | [“” “”] |
| 5000 | 0.50 | 1 | [“eat 12” “energy <= 0”] |
| 10,000 | 0.50 | 1 | [“” “”] |
| 20,000 | 0.50 | 1 | [“” “”] |
| 5000 | 0.10 | 5 | [“eat –5” “(ticks mod 2)=0”] |
| 10,000 | 0.10 | 5 | [“eat 12” “true”] |
| 20,000 | 0.10 | 5 | [“eat 10” “(ticks mod 2)=0”] |
| 5000 | 0.20 | 5 | [“eat 10” “true”] |
| 10,000 | 0.20 | 5 | [“eat 10” “(ticks mod 2)=0”] |
| 20,000 | 0.20 | 5 | [“eat 10” “energy <= 0”] |
| 5000 | 0.50 | 5 | [“eat 12” “(ticks mod 2)=0”] |
| 10,000 | 0.50 | 5 | [“eat 12” “true”] |
| 20,000 | 0.50 | 5 | [“” “”] |
| 5000 | 0.10 | 10 | [“eat 12” “(ticks mod 2)=0”] |
| 10,000 | 0.10 | 10 | [“eat 8” “true”] |
| 20,000 | 0.10 | 10 | [“eat 10” “(ticks mod 3)=0”] |
| 5000 | 0.20 | 10 | [“eat 10” “(ticks mod 2)=0”] |
| 10,000 | 0.20 | 10 | [“eat 4” “energy <= 0”] |
| 20,000 | 0.20 | 10 | [“eat 10” “true”] |
| 5000 | 0.50 | 10 | [“eat 4” “true”] |
| 10,000 | 0.50 | 10 | [“eat 16” “energy <= 0”] |
| 20,000 | 0.50 | 10 | [“” “”] |

the selected institutional arrangements and few signs of overuse. Especially relevant is the quasi-optimal use of the resource in the low resource condition, with withdrawal often approximating the maximum sustainable yield keeping the resource at intermediate levels under a majority of the selected institutions.

## 4.2. Institutions

Even when the institutional emergence option was enabled, agents only created an institution 2/3 of the times. Notably, they only succeeded in doing it when the proportion of agents needed to change the current institution (the threshold for institutional change parameter) was lower than one. The institutional emergence time parameter instead showed a relatively small effect. Finally, the agents never created an institution when $K$=20,000 and $r$=0.5, i.e. when the resource was so abundant and rapidly replenishing that no institution was actually needed to the model satisfaction threshold.

It is interesting to note how their institutions are updated to the environment. Table 4 shows the most common institution for each combination of $K$, $r$ and energy consumption. The amount of energy "consumed" tends to increase with both the resource availability and the agents' requirements, while the modal institution becomes the "open access" one ([“” “”]) for the highest values of *K*, *r*, especially under low energy consumption requirements.

To better analyse the changes in the institution due to different resource availability, we separated the institutions recorded at the end of the simulation into its *aim* and *condition* statements. Figure 3 presents the resulting distribution under both a relatively low and a relatively high resource availability.

When the resource is scarce, agents select relatively high withdrawals at distant intervals. This strategy clearly allows the resource to replenish between

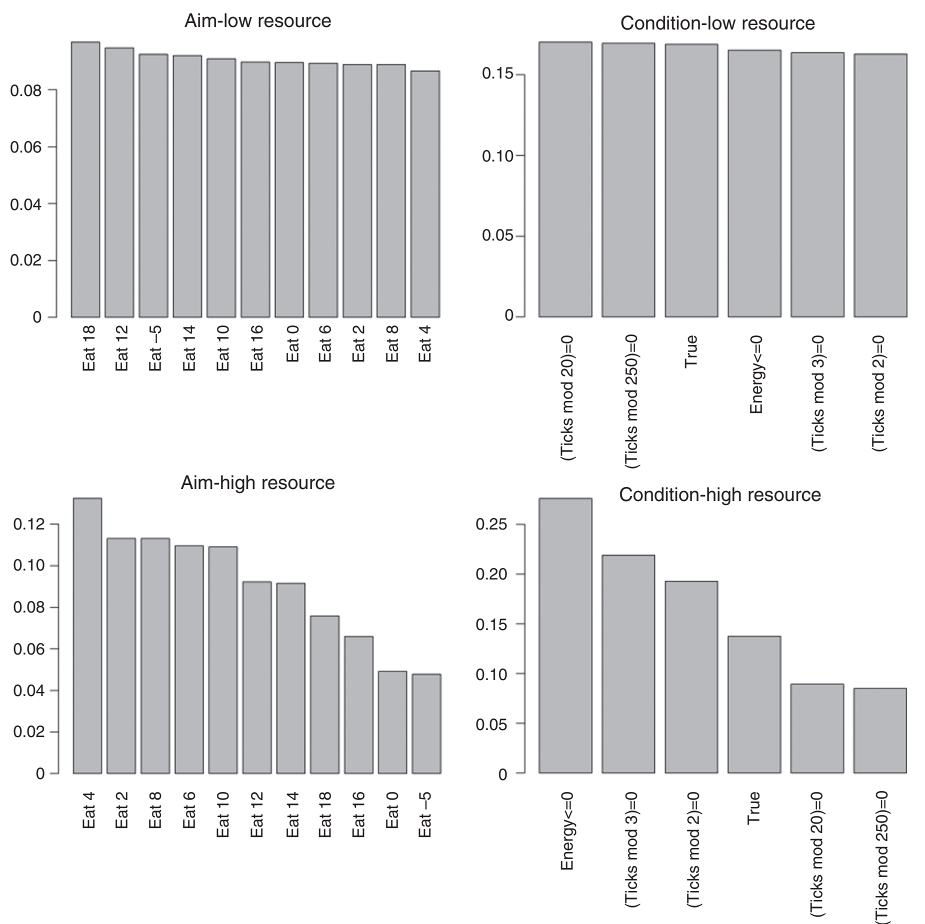


*Figure 3: Distribution of the Aim and Condition statements under low and high resource condition. Low resource is defined as K=5000, r=0.1 and energy.consumption=10. High resource is defined as K=20,000, r=0.1 and energy.consumption=1.*

two different consumption steps. This said, the almost uniform distribution of different insitutions visible in the upper row of Figure 3 testifies the difficult adaptation of agents to a scarcity situation, where easy solutions are not available to simultaneously have enough energy for all and the resource kept at sustainable levels.

On the contrary, when the resource is abundant, relatively small but frequent withdrawals are consistently selected. In a majority of the cases, agents are simply allowed to consume a small amount of resource either when their energy becomes zero (condition: "energy ≤0") or even in every time step (condition: "true"). This allows them to maintain an optimal level of energy without degrading the resource at a level beyond its renewal capacity.

## 5. Discussion and conclusion

In this paper, we presented a preliminary model based on the ADICO grammar of institution showing that an institution emerging through collective behaviour without centralized planning can help the management of common pool resources even without assuming advanced cognitive capacities for the agents. More specifically, the main insight given by the model is the fact that simple micro-level behavioural mechanisms (imitation+random exploration of the strategy space) represent a sufficient condition to promote well adapted institutional arrangements leading to a sustainable management of the commons. However, this can only happen as long as some collective-choice arrangements exist, as emerges from the comparison between simulation settings where building an institution was possible vs. the ones where this was not allowed.

Consistent with many empirical findings (e.g. Ostrom 1990, 2005; Anderies and Janssen 2013), we found that, in systems where institutional development was possible, both the agents' payoffs and the resource condition improved in comparison with situations where the agents only followed their own strategies. This result is also consistent with the work of Smajgl et al. (2008), who also modelled rule changes in social systems using the ADICO structure. However, while they modelled the selection of agents actions and global rules as two separate behavioural mechanisms in the system, we considered the emerging rules as ones that are the result of an aggregation process of the "beliefs" of agents (i.e. their individual strategies). Furthermore, agents' behaviour and decision making in (Smajgl et al. 2008) was defined through internal and external variables such as incentives, motivation, goals and environmental conditions. In the model presented in this paper, agents are cognitively simpler and either randomly choose new behaviours or copy others. Another distinction between these two researches is that, while the resource dynamics in (Smajgl et al. 2008) only followed simple rules and presented no inter-temporal links, we explicitly modelled the resource change over time using prevailing bio-economics models and studied how these changes influence the emergence and evolution of rules.

Despite a much higher level of abstraction and the fact that we took an implicit evolutionary (copying, mutation, etc.) perspective, our results remain fully consistent with both the Smajgl's one and with the findings of empirical research. Notably, we were still able to observe institutional dynamics similar to the ones found in empirical settings and to confirm that institutions do indeed contribute to the sustainable management of common pool resource systems. From this point of view, it is important to note that the positive results observed in the model were more an emergent effect of the collective interaction than of the (actually low) cognitive capacity of the individual agents (see Holland 1998).

Especially interesting was the capacity of agents to collectively adapt their institutions to resource availability. For instance, the fact that agents selected institutions allowing them to harvest only at distant intervals of time bears a clear resemblance with discussions going on during CPR experiments, where time-based strategies allowing the resource to replenish were more often discussed and selected under the most challenging conditions (Janssen 2010).

It is worth noting that the model discussed in this paper represents only a starting point in our research on the mechanisms leading to institutional emergence and that there are many dimensions that can still be added to the model. First, as highlighted by Poteete and colleagues (Poteete et al. 2010), although norm emergence has been studied to some extent, the emergence of rules is an area of research that requires special attention. By building a model using the ADICO structure, we focused our attention to the dynamics (or emergence) of rules. This means that, to be able to study rules in a more realistic way, we should at least add cheating and sanctioning mechanisms to our model. Following Ostrom's argument about the process of norms (ADIC statement) evolving into rules (complete ADICO statements including sanctions), we decided that a reasonable first step was to allow norms to emerge in the system with all agents abiding them. Nevertheless, future versions of the model will allow agents to decide whether they would comply with the institution or follow their own individual strategies through simple learning mechanisms. Finally, the current model allows only one institution to emerge at a time. In future versions, coexistence of various institutions, norms and even individual strategies, and their possible conflicts will also be an interesting area to explore. Moreover, cross-sectional and longitudinal data of real-world long-enduring commons management institutions will be use to provide an empirical validation to our model.

## Literature cited

Anderies, J. M. and M. A. Janssen. 2013. *Sustaining the Commons*. Tempe, AZ: Center for the Study of Institutional Diversity, Arizona State University.

Axtell, R. 2000. Why Agents?: On the Varied Motivations for Agent Computing in the Social Sciences. Center on Social and Economic Dynamics, Working Paper No. 17, www.brookings.edu/es/dynamics/papers/agents/agents.pdf

Balbi, S. and C. Giupponi. 2009. Reviewing Agent-Based Modelling of Socio-Ecosystems: A Methodology for the Analysis of Climate Change Adaptation and Sustainability. *University Ca'Foscari of Venice, Dept. of Economics Research Paper Series* (15_09).

Bonabeau, E. 2002. Agent-Based Modeling: Methods and Techniques for Simulating Human Systems. *Proceedings of the National Academy of Sciences* 99(suppl 3):7280–7287.

Bravo, G. 2011. Agents' Beliefs and the Evolution of Institutions for Common-Pool Resource Management. *Rationality and Society* 23(1):117–152.

Bravo, G., F. Squazzoni, and R. Boero. 2012. Trust and Partner Selection in Social Networks: An Experimentally Grounded Model. *Social Networks* 34(4):481–492.

Crawford, S. E. and E. Ostrom. 1995. A Grammar of Institutions. *American Political Science Review* 89:582–600.

Deadman, P., E. Schlager, and R. Gimblett. 2000. Simulating Common Pool Resource Management Experiments with Adaptive Agents Employing Alternate Communication Routines. *Journal of Artificial Societies and Social Simulation* 3(2):2.

Epstein, J. M. 1999. Agent-Based Computational Models and Generative Social Science. *Generative Social Science: Studies in Agent-Based Computational Modeling* 4(5):4–46.

Falk, A., E. Fehr, and U. Fischbacher. 2002. Appropriating the Commons: A Theoretical Explanation. In *The Drama of the Commons*, eds. E. Ostrom, T. Dietz, N. Dolsak, P. C. Stern, S. Stonich, and E. U. Weber, 157–192. Washington, DC: National Academy Press.

Hardin, G. 1968. The Tragedy of the Commons. *Science* 162(3859):1243–1248.

Hedström, P. 2005. *Dissecting the Social: On the Principles of Analytical Sociology*. Cambridge: Cambridge University Press.

Holland, J. H. 1998. *Emergence. From Chaos to Order*. New York: Basic Books.

Jager, W. and M. A. Janssen. 2003. Using Artificial Agents to Understand Laboratory Experiments of Common-Pool Resources with Real Agents. In *Complexity and Ecosystem Management: The Theory and Practice of Multi-Agent Systems*, ed. M. A. Janssen, 75–102. Cheltenham: Edward Elgar.

Janssen, M. A. 2010. Introducing Ecological Dynamics into Common-Pool Resource Experiments. *Ecology and Society* 15(2):7.

Janssen, M. A. and E. Ostrom. 2006a. Adoption of a New Regulation for the Governance of Common-Pool Resources by a Heterogeneous Population. In *Inequality, Cooperation and Environmental Sustainability*, eds. J.-M. Baland, P. Bardhan, and S. Bowles, 60–96. Princeton: Princeton University Press.

Janssen, M. A. and E. Ostrom. 2006b. Empirically Based, Agent-Based Models. *Ecology and Society* 11(2):37.

Janssen, M. A., R. L. Goldstone, F. Menczer, and E. Ostrom. 2008. Effect of Rule Choice in Dynamic Interactive Spacial Commons. *International Journal of the Commons* 2(2):288–312.

Macy, M. W. and R. Willer. 2002. From Factors to Actors: Computational Sociology and Agent-Based Modeling. *Annual review of sociology* 28:143–166.

North, D. 1990. *Institutions, Institutional Change and Economic Performance*. Cambridge, UK: Cambridge University Press.

North, D. C. 2005. *Understanding the Process of Economic Change*. Princeton, NJ: Princeton University Press.

Ostrom, E. 1990. *Governing the Commons. The Evolution of Institutions for Collective Action*. Cambridge: Cambridge University Press.

Ostrom, E. 2005. *Understanding Institutional Diversity*. Princeton, NJ: Princeton University Press.

Ostrom, E. 2006. The Value-Added of Laboratory Experiments for the Study of Institutions and Common-Pool Resources. *Journal of Economic Behavior & Organization* 61:149–163.

Ostrom, E. 2007. A Diagnostic Approach for Going Beyond Panaceas. *Proceedings of the National Academy of Sciences* 104(39):15181–15187.

Ostrom, E., R. Gardner, and J. Walker. 1994. *Rules, Games, and Common-Pool Resources*. Ann Arbor: The University of Michigan Press.

Ostrom, E., T. Dietz, N. Dolšak, P. C. Stern, S. Stonich, and E. U. Weber, eds. 2002. *The Drama of the Commons*. Washington, DC: National Academy Press.

Poteete, A. R., M. A. Janssen, and E. Ostrom. 2010. *Working Together: Collective Action, the Commons, and Multiple Methods in Practice*. Princeton, NJ: Princeton University Press.

Railsback, S. F. and V. Grimm. 2005. *Individual-Based Modeling and Ecology*. Princeton: Princeton University Press.

Railsback, S. F. and V. Grimm. 2012. *Agent-Based and Individual-Based Modeling: A Practical Introduction*. Princeton: Princeton University Press.

Smajgl, A., L. R. Izquierdo, and M. Huigen. 2008. Modeling Endogenous Rule Changes in an Institutional Context. *Advances in Complex Systems* 11(2):199–215.

Squazzoni, F. 2012. *Agent-Based Computational Sociology*. Chichester: John Wiley & Sons.

Walker, J., R. Gardner, and E. Ostrom. 1990. Rent Dissipation in a Limited Access Common-Pool Resource: Experimental Evidence. *Journal of Environmental Economics and Management* 19:203–211.

Watts, D. J. and S. H. Strogatz. 1998. Collective Dynamics of 'Small-World' Networks. *Nature* 393:440–442.

Wilensky, U. 1999. *Netlogo*. Evanston, IL: Center for Connected Learning and Computer-Based Modeling, Northwestern University.

Wilensky, U. and W. Rand. 2015. *An Introduction to Agent-Based Modeling: Modeling Natural, Social, and Engineered Complex Systems with NetLogo*. Cambridge, MA: The MIT Press.